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Letter to the Editor

The Cl 2236–04 lens cluster

Looking for a third gravitational image?

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Abstract. We present deep imaging and spectroscopy of three blue objects in the Cl2236-04 cluster-lens which follow-up the discovery of a bright arc in the center of the cluster (Melnick *et al.*, 1993), and the model of the matter distribution of this lens (Kneib *et al.*, 1993). The redshift measured for the predicted counter-image of the arc is found to be $z = 1.334$ instead of $z = 1.116$ observed for the arc. This proves that these are not multiple images of the same source. A new model is presented. The source of the arc is reconstructed and shows a bimodal shape, resembling two merging galaxies. This explains the velocity gradient seen in the arc and allows us to predict the redshifts of some of the arclets detected in the cluster.

Key words: gravitational lensing – galaxies: clusters: individual Cl2236-04 – galaxies: distances and redshifts

1. Introduction

Gravitational lensing has become a powerful tool to study both the mass distribution of galaxies clusters and the properties of high redshift galaxies. The multiple images inversion method had been shown to give very strong constraints on the total matter distribution in clusters and, if the model is sufficiently constrained, to derive the redshift distribution of the arclet population (Kneib *et al.*, 1994 and references therein). Clearly, therefore, the detection of arcs and arclets in many cluster-lenses of different dynamical states and at different redshifts is of considerable importance (Fort & Mellier 1994) to get a comprehensive view on the dark matter distribution and on the redshift distribution of background galaxies. At the beginning of the lensing age cluster lens candidates at moderate redshift ($z \approx 0.3$) were selected by their richness, but more recently newly discovered X-ray clusters and strong radio emitters have allowed us to probe cluster-lenses at higher redshifts.

The Cl2236-04 lens was originally discovered by Melnick *et al.* (1993) during a program of optical identification of the Ooty sample of optically faint radio sources with ultra-steep radio spectra (Gopal-Krishna *et al.*, 1992). This cluster ($z = 0.56$) is one of the most distant known lenses along with 3C220.1, $z = 0.62$ (Dickinson, private communication), and MS2053.7-0449, $z = 0.58$ (Luppino and Gioia, 1992). A theoretical model of the Cl2236-04 cluster was presented by Narasimha and Chitre (1993), who pointed out that such "straight" arc can be produced by a source located on a lip caustic. They also stressed the importance of the velocity gradients along these arcs as a new type of constraint. At the same time an alternative model was presented by Kneib *et al.* (1993), based on more recent deep images in the B and R bands. This distribution model assumed that the arc (clearly formed by two images, $A1_1$ and $A1_2$) has a counter-image $A1_3$ (see Fig. 1). This assumption was made because the three images showed the same color ($B - R = 1.4$).

In this *letter* we present new observations of Cl2236-04 obtained in order to confirm the predictions of the model. We find, however, that the redshift of the putative third image is much higher than that of the main arc, which leads us to consider alternative models. We succeeded to find a simple model without counter-image that can reproduce the arc and its velocity gradient. The reconstructed source shows a bimodal shape which, together with the observed velocity gradient, confirms the suggestion of Melnick *et al.*, (1993) that the arc is in fact the highly magnified image of two merging galaxies at $z = 1.116$. Finally, we use the model to predict the redshift of some of the arclets detected in deep images of the cluster.

2. Observations and Results

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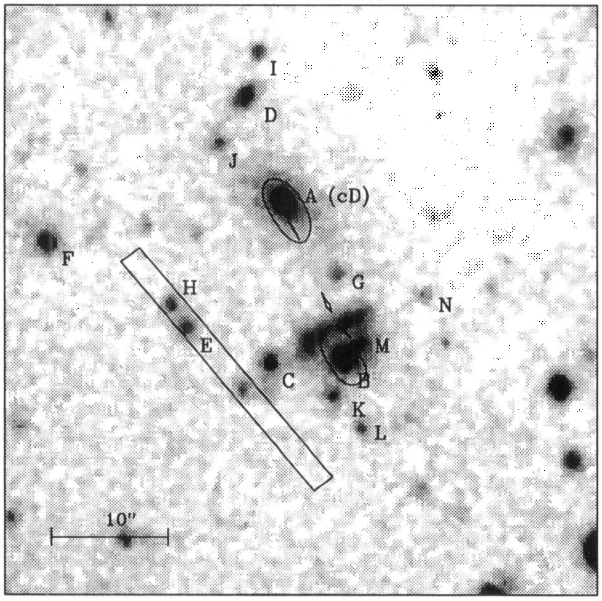

Fig. 1. R image (2400s) of the cluster-lens Cl2236-04, the effective position of the slit is showed. Critic and caustic lines at $z = 1.116$ are showed.

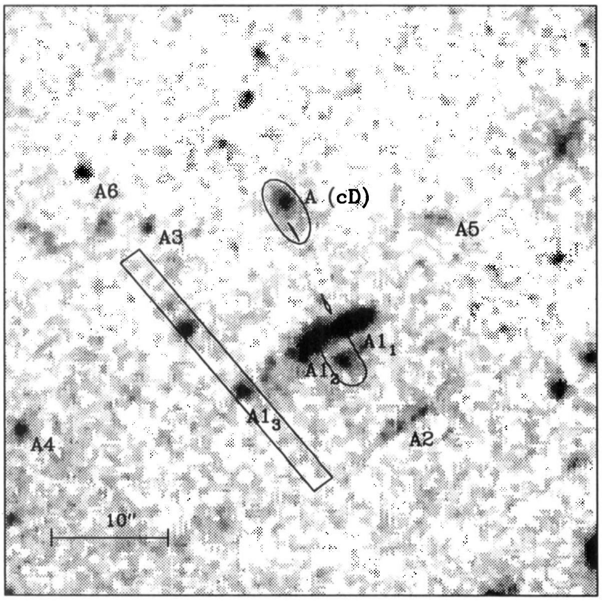

Fig. 2. B image (4800s) of the cluster-lens Cl2236-04, the effective position of the slit is showed. Blue objects in the field are showed. Critic and caustic lines at $z = 1.116$ are showed.

2.1. Photometric Observations

We review briefly the July 1992 NTT/SUSI observations also discussed in Kneib *et al.* (1993). The detector was a TEK1024 CCD binned 2×2 to a pixel size of 0.246″. Exposures of 40min in R (4×600s) and 80min in B (4×1200s) were taken.

At least six very blue objects of almost the same colors as the main arc ($A1$) were detected in the central part of the cluster ($1' \times 1'$), that may correspond to high redshift sources. In particular, a second faint blue arc ($A2$) about 6″ long was detected (Figure 2). The other blue objects noted ($A1_3$, $A2$, $A3$, $A4$, $A5$, and $A6$) are slightly elongated but only barely resolved.

2.2. Spectroscopic Observations

The spectroscopic data presented here were taken with EMMI at the ESO New Technology Telescope in September 1993. The red low dispersion mode was used configured with a long, 2″ wide, slit, grism #4 (6000-9300Å, 3.6 Å/pix), and a Loral 2048 CCD. Three exposures of 3600s were obtained. The slit was oriented to cover $A1_3$, the assumed counter-image, and the two faint galaxies E and H (notation of Kneib *et al.,* 1993; Fig. 1 and 2).

The resulting spectrum of the $A1_3$ object corrected for instrumental effects is shown in Figure 3. The spectrum is flat with a strong emission line at 8700Å. This feature, which is clearly visible in the three frames, is identified with [OII]λ3727 at a redshift of $z = 1.334$.

For the spectra of objects E and H, no strong emission lines are clearly present (Figure 4). The spectrum

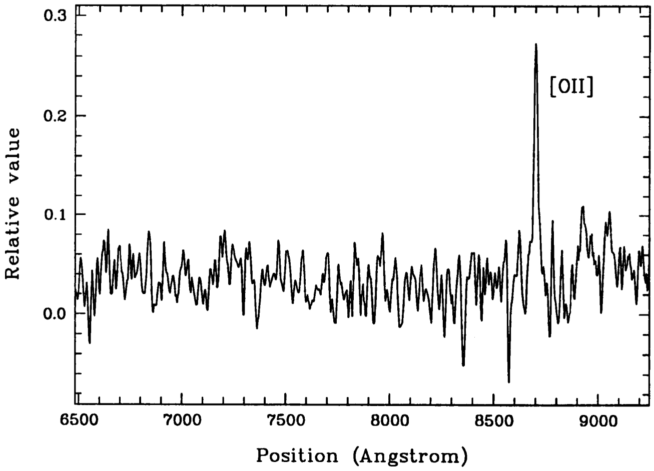

Fig. 3. Spectrum of the $A1_3$ object showing the identified spectral feature.

of galaxy E is rather flat suggesting a high redshift while the spectrum of H is redder with well detected continuum. Weak emission features that can be identified as [OIII] and Hβ suggest that this is a cluster member at a redshift of $z \sim 0.55$.

2.3. Where is the Third Component?

The definitive result that the object $A1_3$ is not the third image of the arc invalidates the lens-models presented by Narasimha and Chitre (1993), and Kneib et al., (1993). Shall we continue to *look for a third image*? $A1_3$ was the only reasonable candidate because of its color and rela-

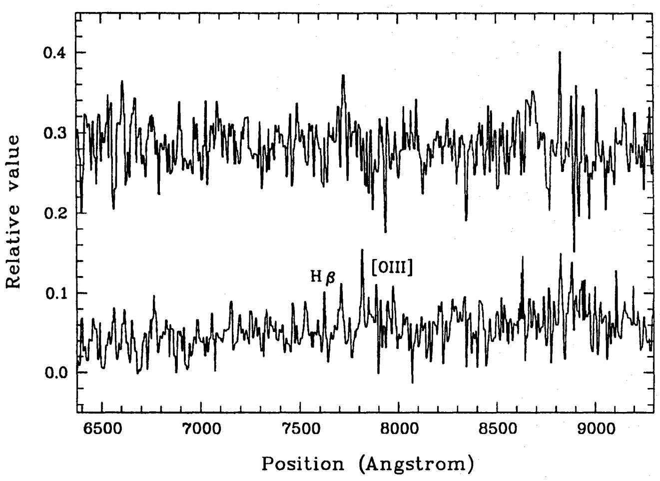

Fig. 4. Spectra of E (top) and H (bottom) galaxies, no strong emission lines are detectable.

tive proximity to the main arc. As shown by Kneib *et al.* (1993), there is no other obvious candidate within a circle of 20″ radius around the arc. Thus, either the third image is too faint and therefore not detected, or there is no counter-image for the arc. The latter possibility is the most attractive: a desamplified counter-arc is not favoured because it needs clump of purely dark matter to explain such a configuration. In fact, we must keep in mind that we are dealing with extended sources (that can present substructures) observed with limited resolution. Hence, if the source lies exactly on the caustic, with a size of the order of the caustic size, no unique conclusions can be reached about the final shape of the deformed image. Indeed, we can observe an "apparently two-image" arc without counter image. In the following section we present such a mass distribution model that reproduces the Cl2236-04 arc without a counter image.

3. A New Model

3.1. Model of the Arc

Cl2236-04 shows two bright galaxies: A (R=19.4), and B (R=19.7). The giant elliptical galaxy A (with an extended envelope) is a radio emitter and is the central galaxy of the cluster. The arc lies between these two galaxies closer to B. It is almost straight with a slight curvature towards galaxy B. This suggests that there is a clump of mass around A with a perturber around B.

From the results of our previous models of giant arcs in other clusters (MS2137: Mellier *et al.* 1993, A370: Kneib *et al.* 1993, A2218: Kneib *et al. in preparation*), we will make the reasonable assumption that clumps of matter follows the geometrical distribution of light of the central giant elliptical galaxies, with center position [x,y], orientation (θ), and ellipticity (ε) similar to those of the galaxies (A: [0″, 0″], $\varepsilon = 0.37$, $\theta = -42°$; B: [4.8″, −14.0″], $\varepsilon = 0.14$, $\theta = -51°$). These assumptions reduce the number of free parameters and allow us to model the arc and the mass distribution.

We used the lens-tool program developed by Kneib (1993). The mass distribution used is the pseudo-elliptical isothermal sphere (Kovner *et al.*, 1993) to account for large ellipticity. In this cluster the strongest constraint to model the mass distribution is the shape and the luminosity of the arc (no other possible multiple images were found in the center of the cluster). Weaker constraints are provided by the velocity gradient along the arc: which does not favour a 'fold-arc' model (in a 'fold' configuration the velocity curve is expected to be symmetric), and by the properties of the other arclets detected: which give the shear-field at larger distance from the center. Therefore, to model the mass distribution, we used a source reconstruction method (Kochaneck *et al.*, 1989, Kochaneck & Narayan 1992). We find that only a small part of the arc can indeed be multiply imaged, which leads to slow convergence. We accelerate convergence by assuming that the source is compact.

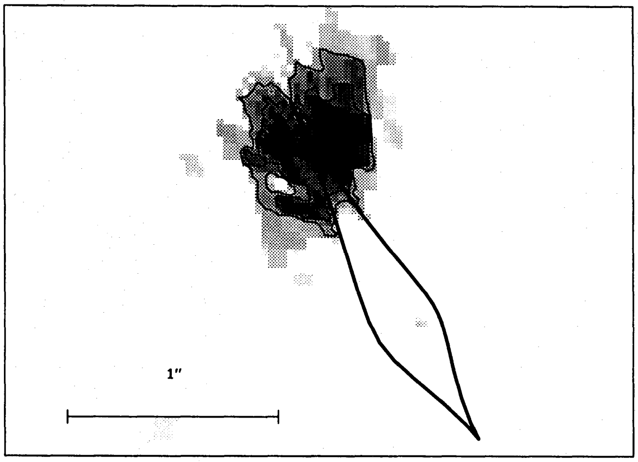

Fig. 5. Image reconstruction of the source at $z = 1.116$; caustic line is represented by a full line.

For the best model the core radius (r_c) and the 3D central velocity dispersion (σ_0) for the two clumps are $r_c = 7''$ ($52h^{-1}$ kpc), σ_0=610 kms^{-1} for clump A, and $r_c = 3''$ ($22h^{-1}$ kpc), σ_0=390 kms^{-1} for clump B. (H_0=50h kms^{-1}Mpc^{-1} and Ω_0=1). The iso-mass densities of this model are shown in Figure 6 which also shows the direction of the shear. The reconstructed image of the source (Figure 5) shows a bimodal structure. The two peaks are located on either side of the lip caustic. When magnified by the lens they are stretched apart making the shape of the observed arc. Higher resolution images (HST images) should confirm and improved the resolution of the final reconstruction.

3.2. Velocity Gradient and Redshift Estimate

With this new model it is now much easier to understand the velocity gradient along the arc. The two "merging" images are just two merging galaxies with opposite velocities of about 100 kms^{-1}.

The separation found (in the reconstructed image) between the two merging galaxies is $\sim 0.2''$ or $1.7h^{-1}$ kpc. The amplification of the source is equal to 16.6, corresponding to a magnitude enhancement of $\Delta m = 3.05$ magnitudes. The deduced magnitudes of the source of the arc are then R=24.2 and B=25.6. The blue color of the arc is explained by the star formation triggered by the merging of the two galaxies.

Using the method developed in Kneib *et al.* (1994), we are able to derive an estimate of the redshift of other lensed objects in the cluster assuming the mass model is correct. For this purpose one needs to know as precisely as possible the ellipticity and orientation of the arclets. In our frame it is possible to determine a secure estimate of the ellipticity and orientation for $A1_3$ (a=0.70,b=0.48,θ=-59.8), and $A2$ and $A3$ (a=0.47, b=0.41, θ=75.5). The values for the major and minor axis of the ellipses (a,b) given here are measured directly on the B frame. Correcting (a,b) from the seeing effect and inverting the lens we find for the arc $A2$ (z >1.5) and for arclets $A1_3$ $z = 1.35 \pm 0.3$ (value that confirms the mass distribution), $A3$ $z = 0.9 \pm 0.25$. The other arclets are too faint or too small to derive reliable estimates of their ellipticity, and therefore to infer their redshifts. As in Kneib *et al.* (1994) we found that most of the background blue galaxies are at redshift lower than 1.5.

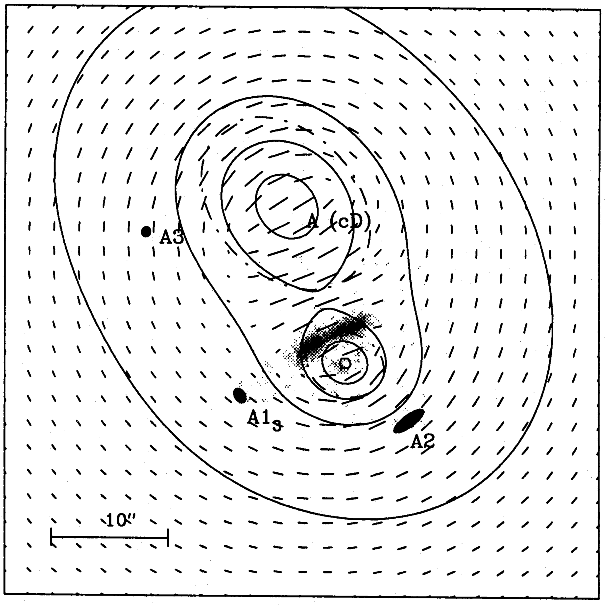

Fig. 6. Mass distribution of the model, with the field of deformation at redshift 1.116. Position and elongation of the arclets are shown by ellipses. The giant arc is shown by contours.

4. Conclusions

The observations of the cluster Cl2236-04 presented in this paper shows that the object $A1_3$ is definitively not the counter-image of the main arc but the lensed image of a galaxy at $z = 1.334$. A new mass distribution model is proposed to explain the shape, the luminosity, the velocity gradient of the arc and the elongation of the $A1_3$ arclet. It also predicts the redshift range of two arc(let)s.

Our results confirm the suggestion made by Melnick *et al.*, (1993), on the basis of the "rotation curve" of the arc, that the arc is a highly magnified image of a distant merger system. Clearly, as stressed by Narasimha and Chitre (1993), radial velocity gradients along giant arcs may provide useful constraints to choose between different lens models.

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